A Hot Electron Microcalorimeter for X-Ray Detection Using a Superconducting Transition Edge Sensor With Electrothermal Feedback

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We investigate a hot-electron microcalorimeter for x-ray detection. The x-ray absorber consists of a normal metal film which is in thermal and electrical contact with a superconducting transition-edge sensor. The superconducting transition-edge sensor is formed by a proximity-effect bilayer of aluminum and silver, with a sharp superconducting transition near 100 mK. Energy from x-rays absorbed in the normal film is removed by a reduction of the Joule heating in the proximity bilayer due to electrothermal feedback, and measured using a SQUID. The feedback mode of operation allows the measurement of incident energy with no free parameters and should lead to improvement in detector resolution over existing hot electron microcalorimeters.

We are developing hot-electron microcalorimeters to use as high resolution x-ray detectors for materials science and astrophysics applications. These devices consist of a normal metal film to absorb the x-rays, and a thermometer to measure the temperature of the electrons in the absorber. The use of a normal metal absorber leads to rapid and efficient thermalization of the incident x-ray. The low temperature of operation (~ 100 mK) leads to a small thermal conductance between the electrons and phonons in the absorber, effectively confining the interaction energy to the electron system during the pulse duration.

Previous work has explored the use of a superconductor-insulator-normal metal (SIN) tunnel junction to measure the temperature of the electrons in the absorber [1,2]. In this work we investigate the use of an Electrothermal Feedback Transition Edge Sensor [3] (ETF-TES) as the thermometer, a technology that is also being applied to dark matter detection [4,5]. We present an overview of the extreme electrothermal feedback operation of such a device, describe our recently developed aluminum-normal metal proximity effect transition edge sensors, and detail our first results indicating stable biasing conditions in the extreme electrothermal feedback regime.

In the ETF-TES, a superconducting film is voltage biased, and the current through it is measured with a SQUID (see Fig. 1). The substrate is cooled to well below the transition temperature. As the film cools, its resistance drops, and the Joule heating increases. When the Joule heating matches the heat loss into the substrate, a stable equilibrium is established. Thus, the detector self-biases on its transition. When an x-ray interacts in the absorber, it is rapidly thermalized, causing an increase in the temperature of the absorber and the ETF-TES. The rise in temperature causes an increase in the film resistance, and hence a decrease in the Joule heating. The heat from the x-ray interaction is removed by the reduction in film Joule heating with an effective time constant which is faster than the intrinsic thermal time constant of the system by the factor[3] $1+a/5$, where a is the "logarithmic sensitivity," $d\log R/d\log T$, a unitless measure of the sharpness of the superconducting transition.

When the effective time constant is short compared to the intrinsic time constant, the detector is operating in the extreme electrothermal feedback regime where effectively all the heat is removed by the reduction in feedback joule heating, rather than escaping into the substrate. Then the x-ray energy deposited in the film is simply the integral of the reduction in feedback Joule heating, or the bias voltage multiplied by the integral of the change in the SQUID current. This feedback process thus allows the direct measurement of energy collection efficiency [3]. This measurement has no free parameters, and so may be compared directly to the incident energy.

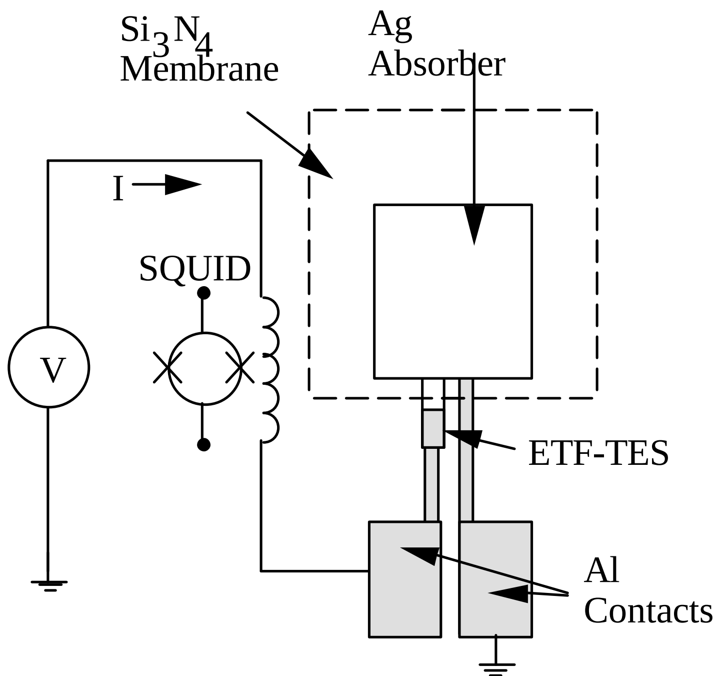

Fig. 1. The electrical bias circuit for the ETF-TES Hot Electron Microcalorimeter and a diagram of its physical layout.

The fundamental energy resolution limit of such a detector has been calculated to be[3] $\Delta E_{FWHM} = 2.36\sqrt{kT^2C(1/a)\sqrt{8n}}$, which is below the FWHM thermodynamic energy fluctuations in the sensor by a factor $\sim 2.5/\sqrt{a}$. For a gold absorber of dimensions 1 mm x 1 mm x 0.5 µm, at a temperature of 100 mK, and a superconducting film with $a = 1000$, this limit corresponds to a resolution of ~ 1.1 eV FWHM. The ETF-TES is thus a very promising candidate technology for x-ray detection.

The ETF-TES requires a superconducting film with a sharp superconducting transition, and a reproducible transition temperature Tc in the region of interest. Since pulse time constants scale as T_c^3, fine tuning of the transition temperature is required to achieve optimal detector performance. When a normal metal - superconductor thin film bilayer is used, the proximity effect will reduce the transition temperature of the superconducting film. By adjusting the relative thicknesses of the two layers, the Tc of the bilayer can be reduced to the desired level.

Proximity bilayers using iridium (T_C = 112 mK) and gold (normal metal) have been used to achieve superconducting transitions in the 30 mK - 100 mK range [6]. Iridium films are, however, extremely difficult to deposit, and the bottom layer in this process must be deposited on a heated substrate. In an effort to develop a technology to easily deposit films with sharp, reproducible transitions usable over a larger temperature range, we have explored a range of proximity bilayers using other superconducting and normal metal films. The normal metals explored include gold, silver, copper, gold/copper alloy, and palladium/copper alloy. The superconductors include aluminum (T_C = 1.1 K) and titanium (T_C = 0.39 K).

Our best results were obtained with aluminum - silver bilayers. We have deposited a number of such bilayers with transition temperatures in the range of interest to us (60 mK - 100 mK), and transition widths < 1 mK (see Fig 2a). When the film thickness is carefully controlled, we achieve a T_C reproducibility of better than 5 mK for these films. These bilayers have been thermally cycled several times over a period of about a month with no change of properties. Although our main interest is in the 60 - 100 mK temperature range, these proximity bilayers would be useful over a much larger range. We have deposited aluminum-normal metal bilayers with very sharp transitions at temperatures as high as 0.57 K (see Fig. 2b).

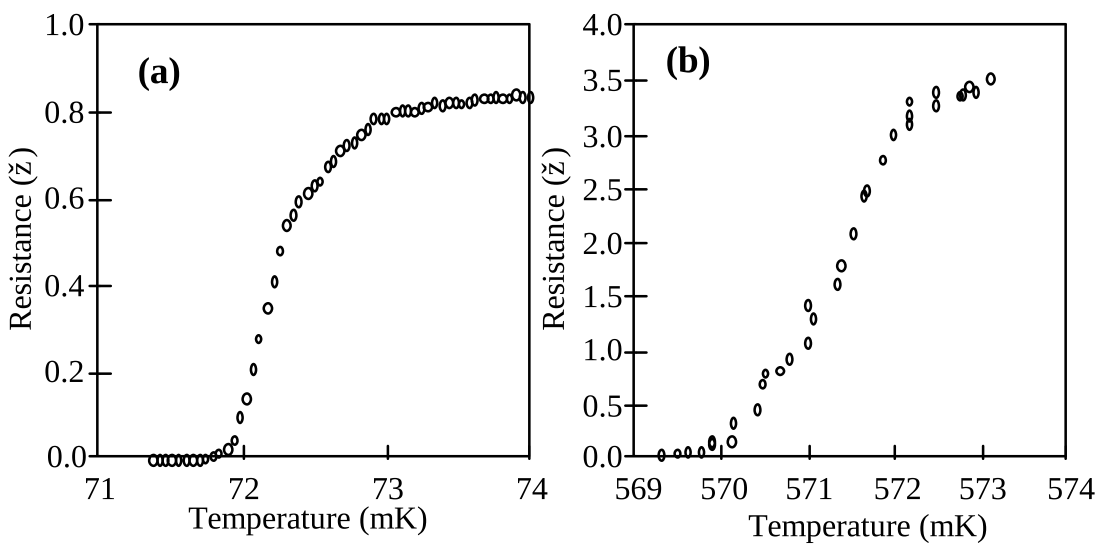

Fig. 2. Superconducting Transitions of Proximity Bilayers. (a) 17 nm Al on 30 nm Ag, (b) 100 nm Al on 50 nm Au/Cu alloy.

The ETF-TES hot-electron microcalorimeter described in this work was fabricated in an e-beam evaporation system using a silicon micromachined shadowmask. The entire structure was fabricated without breaking vacuum. The absorber configuration was similar to that used with SIN tunnel junction thermometers [1].

In order to minimize the absorption of x-rays in the substrate, and to reduce the thermal coupling between the electrons in the absorber and the heat sink, the absorber is deposited onto a freely suspended 0.5 µm thick silicon nitride membrane. The proximity bilayer is deposited on the silicon substrate, and connected to the absorber by a thin silver film. Since the thermal conductivity of the silicon nitride is poor, most of the heat that is deposited in the absorber will flow into the electrons in the proximity bilayer before being removed by electrothermal feedback.

The absorber in the device described in this paper consists of a 0.5 µm thick Ag film with an area of 250 µm x 250 µm. The absorber is thermally connected to the ETF-TES by a 150 nm thick Ag film (see Fig. 1).

Evaporation of the proximity bilayer was conducted after pumping down the chamber to < 7×10^{-5} Pa (5×10^{-7} Torr). The first layer was a silver film 30 nm thick. Without breaking vacuum, a 17 nm thick aluminum film was deposited as the top layer. The resulting film showed a sharp (< 1 mK width) transition at ~ 72 mK (see Fig 2a). Near the base of the transition, a was ~ 1200.

The current through the ETF-TES was measured using a series array of dc SQUIDs [7,8] which provide low noise and high available bandwidth.

The heat flow from the electrons in the proximity bilayer to the silicon substrate scales as $T^5 - T_s^5$ where T is the film temperature and T_s is the temperature of the substrate. If $T_s^5 << T^5$, and the film transition is narrow, the heat flow to the substrate is approximately constant, and the detector is in the extreme electrothermal feedback regime. At equilibrium, this heat flow is matched by the Joule heating, $P_J = IV$.

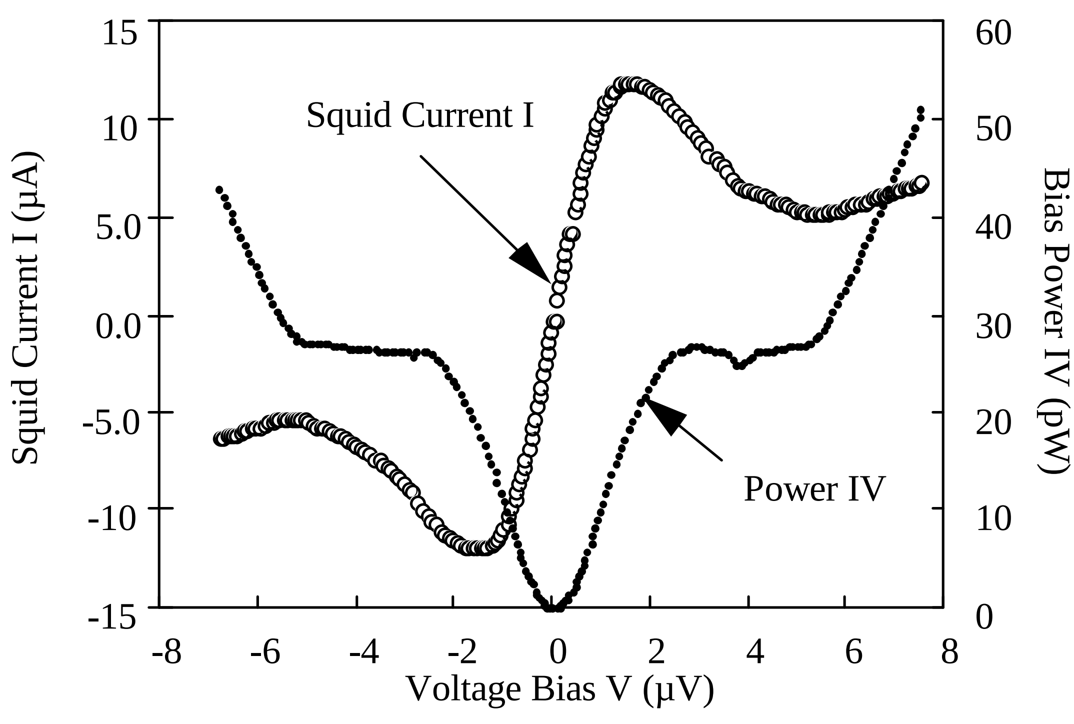

Fig. 3. Current-Voltage Characteristics of the ETF-TES. Open circles: current vs. voltage. Closed circles: power vs. voltage. The power-voltage curve shows a plateau at 27 pW.

In Fig. 3, the current detected by the SQUID is plotted as a function of the bias voltage. At low voltages, the proximity bilayer is superconducting, and the slope of the I-V curve is determined by the resistance of the normal silver film linking the transition-edge sensor to the electrical ground (see Fig. 1). When the bias voltage is increased sufficiently, the superconducting film begins to self bias within its transition, where the product of the current ant the voltage is constant. This region thus has a negative differential resistance, dV/dI. As long as the film stays within its transition, as the voltage is increased, the current decreases to keep the Joule power constant. When the bias voltage is increased sufficiently the bilayer is driven completely normal, and the current begins to rise again with a slope determined by the normal resistance of the film.

In Fig. 3 the Joule power $P_J = IV$ is also plotted as a function of the bias voltage. Here we see that when the film is biased within its transition, the Joule power is indeed constant, and the film is operating in the extreme negative electrothermal feedback regime. When an x-ray deposits energy in the absorber, the ETF-TES will compensate by reducing the current in order to maintain a constant total power load.

In conclusion, we have demonstrated that the aluminum-silver proximity effect technology can produce films with reproducible, sharp transitions. We have shown that the ETF-TES microcalorimeter self-biases according to theory, and that the power dissipation is constant within the transition. The fundamental theoretical limits on the resolution of the ETF-TES are extremely promising. Experiments to determine the response to incident x-rays are currently being conducted.

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